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A review on compressed-air energy use and energy savings

R. Saidur [a,*], N.A. Rahim [b], M. Hasanuzzaman [a]

[a] Department of Mechanical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Department of Electrical Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

Compressed-air systems account for about 10% of total industrial-energy use for few selected countries as found in literatures. Compressed air is typically one of the most expensive utilities in an industrial facility. This paper describes a comprehensive literature review about compressed air energy use, savings, and payback period of energy efficient strategies. This paper compiles latest literatures in terms of thesis (MS and PhD), journal articles, conference proceedings, web materials, reports, books, handbooks on compressed air energy use, efficiency, energy savings strategies. Computer tools for compressed air analysis have been reviewed and presented in this paper. Various energy-saving measures, such as use of highly efficient motors, VSD, leak prevention, use of outside intake air, reducing pressure drop, recovering waste heat, use of efficient nozzle, and use of variable displacement compressor to save compressed-air energy have been reviewed. Based on review results, it has been found that for an electric motor used in a compressed-air system, a sizeable amount of electric energy and utility bill can be saved using high efficient motors and applying VSDs in matching speed requirements. Also, significant amounts of energy and emission are reducible through various energy-saving strategies. Payback periods for different energy savings measures have been identified and found to be economically viable in most cases.

Contents

* Corresponding author. Tel.: +60 3 79674462; fax: +60 3 79675317.
E-mail address: saidur@um.edu.my (R. Saidur).

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Nomenclature

AES	annual energy savings
AEU	annual energy usage
ES_{VSD}	energy savings with the application of VSD
H_{avg_usage}	Annual average usage hours
n	number of motors
P	motor power (kW)
S_{SR}	percentage energy savings associated certain percentage of speed reduction
VSD	variable speed drive
hp	motor's rated horsepower
L	load factor (percentage of full load)
hr	annual operating hours
c	average energy cost (US$/kWh)
E_{std}	standard-motor efficiency rating (%)
E_{ee}	energy-efficient motor efficiency rating (%)
0.746	conversion factor from horsepower to kW
AES_{cs_leak}	annual energy savings by preventing leak (MWh)
%ES	% of energy savings by preventing leak
T	on-load time (min)
t	off-load time (min)
V	m^3
P	kPa
T	minutes
W_R	fractional reduction in compressor work
W_I	work of compressor with inside air (kW)
W_O	work of compressor with outside air (kW)
T_I	the average temperature of inside air (°C)
T_O	the annual average outside air temperature (°C)
AES_{ia}	energy savings associated with the usage of outside intake air temperature
AES_{pd}	energy savings due to pressure drop
FR_i	ratio of proposed power consumption to current power consumption
FR	the horsepower reduction factor
P_{dp}	discharge pressure at proposed operating pressure conditions (kPa)
P_{dc}	discharge pressure at current pressure conditions (kPa)
P_i	inlet pressure (atmospheric pressure) (kPa)
k	ratio of specific heat for air ($k = 1.4$).
HRF	heat recovery factor
ca	air compressor
ANS_i	annualized net dollar savings in i year of air compressor
AS_i	applicable stock in year i of air compressor
CRF	capital recovery factor
d	discount rate (%)
ES_i	energy savings in year i of air compressor
IIC	initial incremental cost for more efficient air compressor
PF	price of fuel
SF	scaling factor
$PV(ANS_i)$	present value of annualized net saving i of air compressor
PEi	percentage of electricity generation in year i of fuel type 1 (%)
Em_{np}	fossil fuel emission for a unit of electricity generation of fuel type 1 (kg)

1. Introduction

Use of compressed air in industry and in service sectors is common as its production and handling are safe and easy. In most industrial facilities, compressed air is necessary to manufacturing. Compressed-air generation is energy intensive, and for most industrial operations, energy cost fraction of compressed air is significant compared with overall energy costs. Yet, there is a vacuum of reliable information on the energy efficiency of a typical compressed-air system [1–6].

As a general rule, compressed air should be used only if safety enhancements, significant productivity gains, or labour reduction, will result as it is very expensive (see Fig. 1). Greenough [7] also reported how to select compressed-air system for an industrial facility.

Annual operating costs of air compressors, dryers, and supporting equipment, can account from 70% [9–11] to 90% [12] of the total electric bill.

Compressed air accounts for as much as 10% of industrial electricity consumption in the European Union [13]. Fig. 2 shows compressed-air energy use in 15 EU countries. Compressed-air systems in China use 9.4% of China's electricity. Compressed air is probably the most expensive form of energy in a plant, because only 19% of its power are usable. In the US, compressed-air systems account for about 10% of total industrial-energy use [14], as in Malaysia [15]. In South Africa, compressed air consumes about 9% of total energy consumption [16,17]. Table 1 shows the industrial application of compressed-air system.

According to the total life cycle costs (LCC), initial investment and maintenance represents only a small portion of the overall cost of

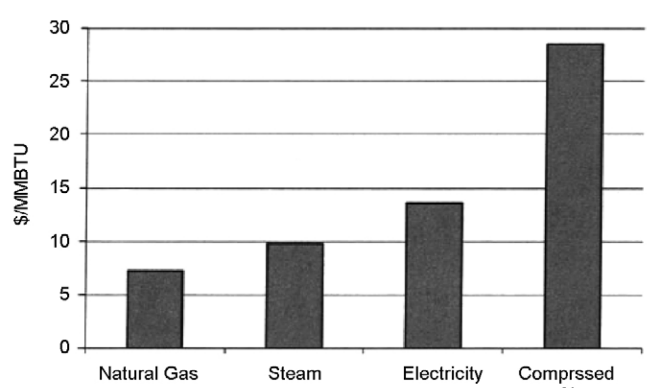


Fig. 1. Cost of energy delivery modes [8].

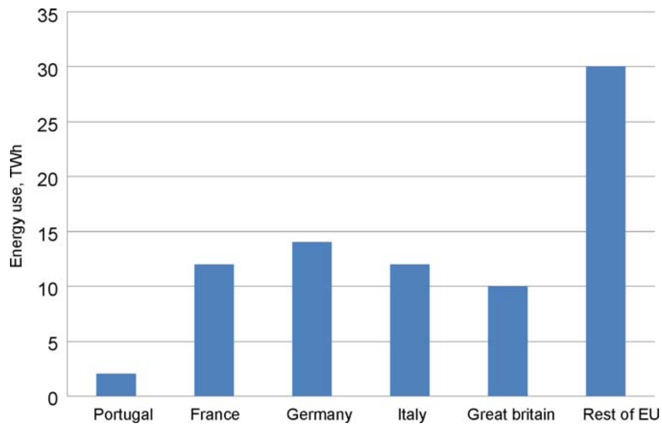


Fig. 2. Compressed-air energy use in 15 EU countries [13].

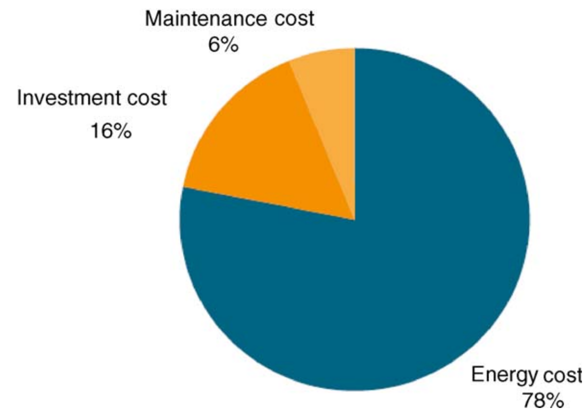


Fig. 3. Life cycle costs of compressed-air energy use [13].

compressed-air equipment, and the power required to operate the compressor is usually 75%, or more, of the annual cost of compressed air, as Fig. 2 shows. Improvement to compressed-air systems can achieve 20–50% energy savings [18]. Over a compressed-air system's lifetime, operating energy is its single greatest cost (see Fig. 3), in many cases exceeding five times the initial equipment cost [19–24].

Two of the most important factors influencing the cost of compressed air are the type of compressor control and the proper compressor sizing. Oversized compressors and compressors operating in inefficient control modes have the highest unit energy and the highest annual operating costs [25–28].

Manufacturers are quick to identify energy (and thus money) losses from hot surfaces and to insulate those surfaces but somehow are not alert towards saving compressed air as they view air to be free; the only time air leaks and dirty air filters get any attention is when air and pressure losses interfere with normal operation of the plant. However, paying attention to compressed-air systems and practising simple conservation measures can save considerable energy and cost. The cost of electric power operating an air compressor continuously for a year is usually greater than the initial price of the equipment. From this perspective, any efforts to reduce energy consumption pay for themselves immediately and produce ongoing savings [9].

Although technology changes improve compressed-air efficiency, institutional and behavioral change, which involves government and public-interest facilitators, produce greater effects. Still, many industrial facilities do not take the time to study the costs involved in the generation of what is probably their most expensive plant utility energy source [2]. Small modifications have been proven to result in large savings and short payback periods. Such modifications include reducing leaks, matching supply with demand, reducing pressure setting if low pressure is adequate, using a smaller compressor at full load instead of a large one at part load, reducing average inlet temperature by using outside air, using waste heat from the cooling fluid to heat the facility in winter, using high-efficiency motors, turning off the compressor at night and during lunch break and using an after cooler, all which impact energy savings [26,29–33].

In this study, the authors give an overview of energy-saving measures, complete with an analysis on potential savings of energy and cost, and simple payback periods. The authors hope that the information, will be useful to policy makers, researchers, and industrial-energy users. It is expected that the review results presented in this paper will create awareness on the potential energy savings of compressed-air systems for industrial-energy users.

2. Methodology

This section explains the energy audit, the data needed for energy analysis, in estimating energy savings and emission reductions by high-efficiency motor, variable speed drive, preventing leak, use of intake air temperature, reducing pressure drop, recovering waste heat and use of efficient nozzle.

2.1. Energy audit

A systematic approach, to monitor industrial-energy consumption and to pin-point sources of wastage, is known as energy audit. An energy audit study helps an organization to understand and analyze its energy utilization and identify areas where energy use can be [34–41] reduced, decide on how to budget energy use, plan and practice feasible energy conservation methods that will enhance their energy efficiency, curtail energy wastage and substantially reduce energy costs. The energy input is an essential part of any manufacturing process and often form a significant part of expenditure of the plant.

Table 1
Industrial sector uses of compressed air [17].

Industry	Example of compressed air uses
Food	Dehydration, bottling, controls and actuators, conveying, spraying coatings, cleaning, vacuum packing
Textiles	Agitating liquids, clamping, conveying, automated equipment, controls and actuators, loom jet weaving, spinning, texturizing
Apparel	Conveying, clamping, tool powering, controls and actuators, automated equipment
Lumber and wood	Sawing, hoisting, clamping, pressure treatment, controls and actuators
Furniture	Air piston powering, tool powering, clamping, spraying, controls and actuators
Pulp and paper	Conveying, controls and actuators
Chemicals	Conveying, controls and actuators
Petroleum	Process gas compressing, controls and actuators
Rubber and plastics	Tool powering, clamping, controls and actuators, forming, mold press powering, injection molding
Stone, clay, and glass	Conveying, blending, mixing, controls and actuators, glass blowing and molding, cooling
Primary metals	Vacuum melting, controls and actuators, hoisting
Metals fabrication	Assembly station powering, tool powering, controls and actuators, injection molding, spraying

Any savings in energy directly adds to the profit of the company. The cost of energy inputs, viz. electricity and fuel are increasing and excessive consumption of energy eat up the profits of the company [31,42].

The energy audit serves to identify all the energy streams in a facility, quantify energy usage, in an attempt to balance the total energy input with its use. An energy audit is thus the key to a systematic approach for decision-making in the area of energy management [43,44]. As a result, the energy audit study becomes an effective tool in defining and pursuing a comprehensive energy management programme. As the focus of the paper is about electric motor energy usage, details of energy audit are also towards electric motor energy management through an energy audit. Numerous studies have been published on energy audit and energy analysis results for different industries [20,26,30,31,33,42,45–68].

2.1.1. Energy audit objectives [34,38,69,70]

Following are the objectives that can be considered for compressed-air energy audit:

- To identify compressed-air energy use in an industry.
- To implement energy savings measures by which individual industry can conserve energy used in their high-energy using equipment/processes such as compressed-air systems.
- To provide a pathway to benchmark energy usage of compressed-air energy in other industries.
- Identify compressed-air energy wastages.

2.1.2. Energy audit process

Energy management requires a systematic approach-from the formation of a suitable team, to achieving and maintaining energy savings. A typical process is outlined in Fig. 4.

2.1.3. Types of energy audit

There can be three types of energy audits [34,35,38,41].

1. Preliminary audit.
2. Single purpose.
3. Comprehensive.

2.1.3.1. Preliminary energy audit. Preliminary audit is conducted in a limited span of time. It focuses on major energy supplies and demands of the industry. The scope of this audit is to highlight energy costs and to identify wastages in major equipment processes it sets priorities for optimizing energy consumption. This type of energy audit checks energy use and energy management in factories.

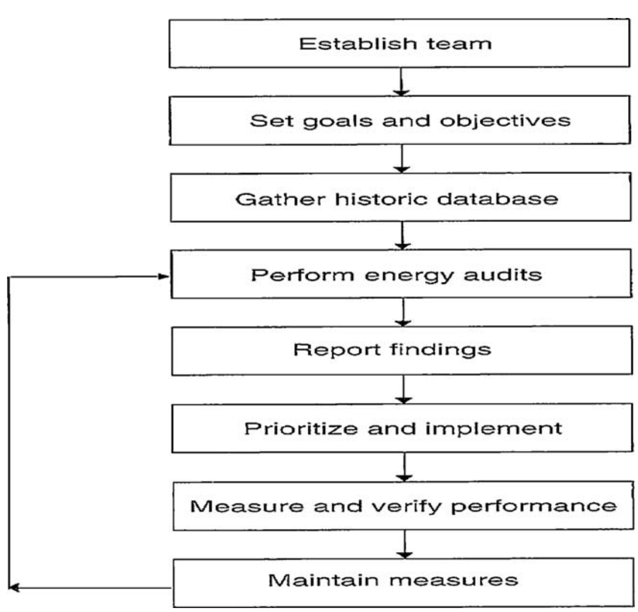


Fig. 4. Typical energy management program [38,44].

The preliminary audit alternatively called a simple audit, screening audit or walk-through audit, is the simplest and quickest type of audit. It involves minimal interviews with site operating personnel, a brief review of facility utility bills and other operating data, and a walk-through of the facility to become familiar with the building operation and identify glaring areas of energy waste or inefficiency.

Typically, only major problem areas will be uncovered during this type of audit. Corrective measures are briefly described, and quick estimates of implementation cost, potential operating cost savings, and simple payback periods are provided. This level of detail, while not sufficient for reaching a final decision on implementing a proposed measures, is adequate to prioritize energy efficiency projects and determine the need for a more detailed audit [71,72]

2.1.3.2. Targeted energy audit. This type of audit provides a detailed analysis on one or more types of projects. The projects analyzed could result from a preliminary audit or vendor or could be selected by the facility staff as needed to repair or upgrade the project. Examples include those that focus only on electric motor energy managements systems in compressed-air system.

2.1.3.3. Detailed energy audit. This covers estimation of energy input for different processes, losses, collection of past data on production levels and specific energy consumption. It is a comprehensive energy audit action plan to be followed effectively by the industry. The scope of this audit is to formulate a detailed plan on the basis of quantitative and control evaluation, to evolve detailed engineering for options to reduce total energy costs, consumption for the product manufactured. This type of audit covers measuring and collecting the detailed data. Energy audit for planning the further service is also included in details energy audit.

2.1.3.4. Detailed energy audit. Detailed energy audit is a quantitative assessment of the extent of rational use of energy and aims at deriving recommendations by not only considering available data but also undertaking instrumented measurements and testing of major energy consuming sub-systems which are sensitive to energy cost of the product.

The objective of the detailed energy audit is to the operations of energy intensive equipment/systems for identification of potential areas wherein energy savings are practically feasible [73,74].

2.1.4. Tools for energy audit

To conduct a detailed energy audit following tools are needed to get the pertinent data for compressed-air energy use [34,35,38,41].

1. Clamp-on power meter: This type of meter help measure power consumption, current drawn, load factor and power factor. The meter should have a clamp-on feature to measure current and probes to gauge voltage so that measurements can be recorded without any disruption to normal operation.
2. Portable tachometer: This meter is useful for measuring the speed of the motor. Optical type tachometer are preferable due to the ease of measurement.
3. Thermocouple sensor: Thermometer/thermocouple sensors are useful to measure the temperature of the energy using machinaries so that level of temperature can be checked whether machine is overheated or not. This will prevent equipment failure or damage. Moreover, temperature gain will cause a motor to consume more energy. Knowing temperature allows the auditor to determine equipment efficiency. Most

commonly used sensors are RTDs and thermistors. The accuracy of these sensors is important. Such temperature sensors need to be connected to a data logger for data storage and analysis.
4. Data logger: Data loggers are used to monitor and log data such as temperatures, motor current, and power. Data loggers are normally portable and can accept different inputs from sensors.
5. Ultrasonic leak detector: This equipment is needed to detect leak in compressed-air systems.

2.1.5. Data needed for a compressed-air energy audit

Following are the most important data that are needed for compressed-air energy analysis [15,45,75,76]:

- load factor;
- production figure;
- power rating;
- power factor;
- efficiency at given LF;
- efficiency adjusted to that at 75% of LF;
- duty factor (hours of operation/year);
- motor load profile;
- utility bill;
- demand uses;
- peak and off peak usage hours;
- mass flow rate of air;
- temperature;
- pressure.

2.2. Energy use of compressed-air systems

Annual energy usage by compressed-air systems can be estimated using Eq. (1) [15,34]:

$$\mathrm{AEU} = \mathrm{hp} \times L \times 0.746 \times \mathrm{hr} \quad (1)$$

2.3. Estimating energy savings, payback periods, and emission reductions

From the literature studied, it was found that compressed-air systems use about 9–10% of total industrial-energy usage for many countries and hence it has the potential for energy savings and emission reduction through the application of various energy-saving strategies. Various industrial energies can be saved in various ways by using machineries with different energy-saving strategies. As motors take up a major share of the total industrial-energy usage (as found in the literatures listed in Table 2), their energy savings can be achieved through the introduction of energy-efficient motors, use of VSD, preventing leakes, use of intake air temperature, reducing pressure drop, use of water heat and use of efficient compressed-air systems.

Details of each of energy savings measures elaborated with mathematical formulation to estimate energy savings and emission reductions along with economic analysis. Fig. 5 shows the energy savings opportunities for compressed-air system [88].

Table 2
Statistics of electric-motor energy use in selected countries.

Country	Energy use (%)	Reference
US	75	[69,77,78]
UK	50	[79]
EU	65	[80–82]
Jordan	31	[83]
Malaysia	48	[15]
Turkey	65	[84]
Slovenia	52	[85]
Canada	80	[86]
India	70	[87]

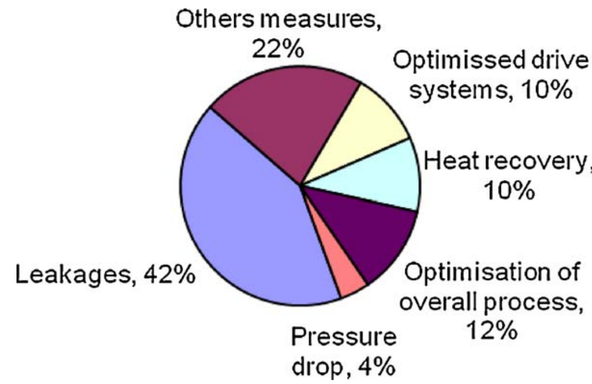


Fig. 5. Different options of compressed-air energy savings.

Fig. 6 shows the energy savings measures and their corresponding savings for different expections (i.e. realized, in preparation, and planned).

Fig. 7 shows the recommended and savings achieved for different energy savings measures for compressed-air systems [46].

2.3.1. Energy savings by using a high-efficiency motor

A high-efficiency motor (HEM) uses low-loss materials to reduce core, and copper, losses. Design changes, better materials, and manufacturing improvements, reduce motor losses, making premium, or energy-efficient, motors, more efficient than standard motors are. Reduced losses mean that an energy-efficient motor produces a given amount of work with less energy input than that required by a standard motor [89].

Several leading electric-motor manufacturers, mainly in USA and Europe, have developed product lines of energy-efficient electric motors that are 2–8% more efficient than the standard motors are [41,90]. Electric motors cannot convert into mechanical energy completely, the electrical energy they take. The ratio of the mechanical power supplied by the motor to the electrical power used during operation is the motor's efficiency. High-efficiency motors cost less to operate than do their standard counterparts. Motor efficiencies range from about 70 to over 96% at full-load rated power [90].

Switching to energy efficient motor driven systems can save Europe up to 202 billion kWh in electricity use, equivalent to a reduction of USD16.3 billion per year in industrial operating costs. It was reported that a reduction of 79 million tons of CO_2 emission (EU-15) or approximately a quarter of the EU's Kyoto target is achievable through energy-efficient motors. This is the annual amount of CO_2 that a forest the size of Finland transforms into oxygen. If industries are allowed to trade these emission reductions based on energy saved, this would generate a revenue stream of USD 3.3 billion per year. For EU-25, the reduction potential is 100 million tons [80].

2.3.1.1. Mathematical formulations to estimate energy savings by using HEMs. Annual energy savings (AES) through replacement of standard efficient motors with highly energy-efficient motors can be estimated by using the methodology described in Refs. [34,91]:

$$\mathrm{AES} = \mathrm{hp} \times L \times 0.746 \times \mathrm{hr} \times \left[\frac{1}{E_{\mathrm{std}}} - \frac{1}{E_{\mathrm{ee}}}\right] \times 100 \quad (2)$$

Annual bill savings associated with the above energy savings can be calculated as

$$\mathrm{Savings} = \mathrm{AES} \times c \quad (3)$$

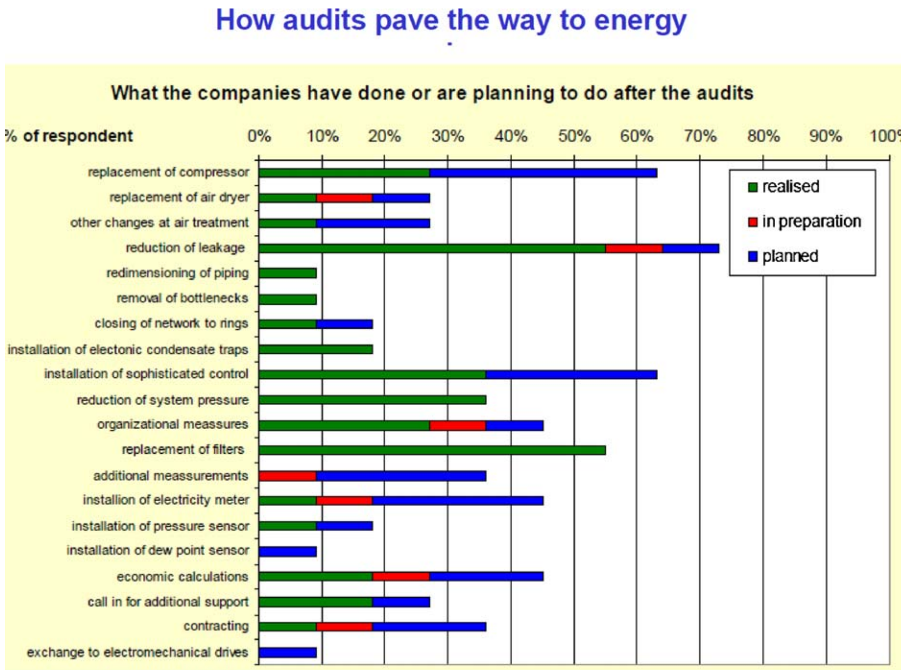


Fig. 6. Energy savings due to audit [13].

Table 3 shows the typical input data needed for electric-motor energy-saving estimation. Table 4 shows the efficiencies of various-capacity motors, against various loads.

2.3.2. Motor's energy savings through variable speed drive (VSD)

Many compressed-air systems are designed to operate at maximum-load conditions. However, most of the systems operate at their full load only for short periods. This often results in many systems operating inefficiently during long periods. The efficiency of such systems can be improved by varying their capacity to match actual load requirements. As all these are variable torque applications, the power required (to drive the pumps or fans) varies with the cube of the speed, and therefore, large power reductions result from small reductions in speed (see Fig. 8). The

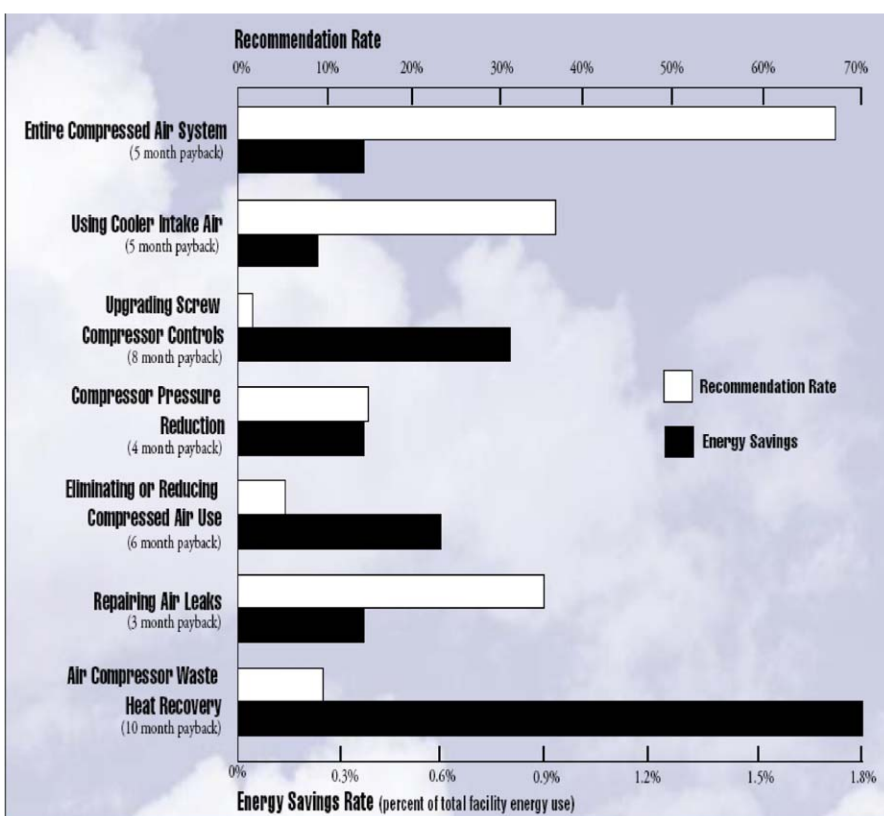


Fig. 7. Energy savings and payback period for different options [46].

Table 3
Input data for motor's energy savings.

Parameters	Value
Average usage hours	6000
Average electricity cost (US$/kWh)	0.064

most common method is the modulation of speed, of the motors, of pumps, compressors, and fans, to vary their capacity by using VSDs [91]. Variable-frequency drives provide continuous control, matching motor speed to the specific demands of the work being performed. Variable-frequency drives are an excellent choice for adjustable speed-drive users because they allow operators to fine-tune processes while reducing costs of energy and of equipment maintenance [35,38,91].

Electric motors are over 90% efficient when running at their rated loads. However, they are inefficient at load-following, or running at part loads. Conventional electric motors typically use 60–80% of their rated input energy, even when running at less than 50% load [35]. It is very important to select an electric motor of suitable power to work efficiently. In general, big-capacity motors are chosen to meet extra-load demands. Big capacities cause motors to work inefficiently at low loads. Usually, motors operate more efficiently at 75% or more of rated load. Because of their big capacity, motors operated at lower than 50% of rated load perform inefficiently, and because the reactive current increases, power factors also decreases. These types of motor do not use energy efficiently because they were chosen for their huge motor power and not according to need. They should be replaced with new, suitable-capacity motors, and when purchasing new motors, energy-saving motors should be preferred [86]. ASDs yield sizable energy savings (15–40% in many cases) and extend equipment life by allowing gentle start-up and gentle shutdown [92].

2.3.2.1. Mathematical formulations to estimate energy savings by using VSD. Many ways can be used to estimate the energy savings from use of VSD in industrial motors for various applications. This paper uses the methods found in [93].

Energy usage of fans and pumps varies with speed raised to the third power, so small changes in speed results in huge changes to energy usage. A motor's energy savings through VSD can be estimated as

$$ES_{VSD} = n \times P \times H_{avg_usage} \times S_{SR} \quad (4)$$

Table 5 shows the potential energy savings from speed reduction, through use of VSD in industrial motors [94]. These data can be been used to estimate a motor's energy savings through use of VSD.

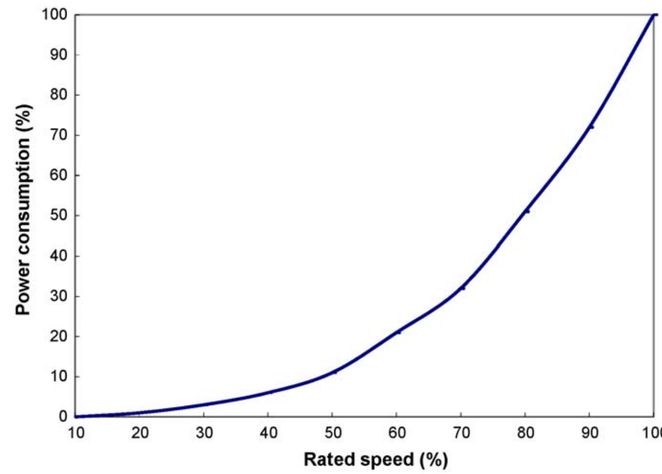


Fig. 8. Relationship between motor's power reduction and rated speed [35].

2.3.3. Energy savings through leak prevention

Leaks can be a significant source of wasted energy in an industrial compressed-air system, sometimes wasting 20–50% of a compressor's output. An unmaintained plant will likely have a leak-rate equal to 20% of total compressed-air production capacity. Other than a source of wasted energy, a leak contributes to other operating losses; it causes a drop in system pressure, making air tools function less efficiently, affecting production [9,95].

In addition to increased energy consumption, leaks can make air tools less efficient and adversely affect production, shorten the life of equipment, lead to additional maintenance requirements and increased unscheduled downtime. Leaks cause an increase in compressor energy and maintenance costs [9].

Air leaks are the single greatest cause of energy loss in manufacturing facilities with compressed-air systems. The cost of compressed-air leaks is the cost of the energy required to compress the volume of lost air, from atmospheric pressure to the compressor's operating pressure. This cost is often significant. The amount of lost air depends on the line pressure, the compressed-air temperature at the point of leak, the air temperature at the compressor inlet, and the area of leak. Air leaks, in general, occur at the joints, flange connections, elbows, reducing bushes, sudden expansions, valve systems, filters, hoses, check valves, relief valves, extensions, and the equipment connected to the compressed-air lines. Total elimination of air leaks is impractical, but 20% leakage rate is considered acceptable. The cost of compressed-air leaks increases exponentially as the

Table 4
Efficiencies of standard, and high-efficiency, motors, against various loads [15,34].

Motor HP	Incremental cost (US$)	Load (50%)		Load (75%)		Load (100%)	
		E_{std}	E_{ee}	E_{std}	E_{ee}	E_{std}	E_{ee}
1	21	70.05	75.28	74.43	79.49	77.00	80.97
1.5	25	76.04	80.06	78.03	81.28	78.50	82.55
2	27	77.20	80.02	79.29	83.07	81.00	83.55
3	60	77.78	82.44	79.87	84.55	81.50	85.01
4	61	81.07	83.69	82.39	85.24	82.90	85.96
5.5	68	81.15	84.35	84.73	86.50	85.30	87.75
7.5	91	84.07	85.51	86.23	87.58	86.61	89.50
15	100	84.92	88.32	86.45	89.85	87.94	90.44
20	111	86.03	88.51	87.58	91.05	88.95	91.64
25	186	87.61	90.26	88.39	91.66	89.50	91.80
30	273	88.43	90.89	89.32	91.73	90.70	91.83
40	371	88.15	90.39	90.54	91.91	90.36	92.85
50	678	89.63	91.16	89.86	92.58	92.06	93.28
60	887	87.89	90.07	91.31	92.09	91.78	93.00
75	1172	88.77	90.86	90.19	92.72	92.44	93.02

Table 5
Potential savings from VSD [93].

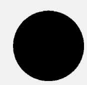
Average speed reduction (%)	Potential energy savings (%)
10	22
20	44
20	61
40	73
50	83
60	89

Table 6
Wasted air and energy for different leak sizes.

Hole diameter (cm)	Wasted air (m^3 per year)	Wasted energy (kWh/year)
0.08	15,670	1,500
0.16	62,890	6,040
0.32	249,290	24,240
0.64	991,500	97,000
0.96	2,237,960	218,500

Note: Based on continuous operation and sharp hole at 689.5 kPa.

Table 7
Cost of waste energy due to leak (source: http://www.nrel.gov/docs/fy03osti/29166.pdf).

	Size	Cost per year
	0.16	$523
	0.32	$2095
	0.64	$8382

Source: http://www.nrel.gov/docs/fy03osti/29166.pdf.

diameter of the leak increases, as Fig. 9 shows compressed-air energy loss due to leak. Leaks should be repaired as soon as is practical, and may easily be located through their hissing when other plant operations are idle. In some situations, it may be necessary to wait for a scheduled plant shutdown. Temporary repairs can often be made by placing a clamp over the leak [9,19,96]. Leaks in compressed-air systems has no benefit and can account for 20-30% of a facility's compressed-air demand [18,97].

Another study [98] as can be seen in Table 6 shows the energy waste due to leakage of compressed-air system. Table 7 shows the cost of energy lost for different sizes of leak.

The best way to detect leaks is to use an ultrasonic acoustic detector, which can recognize the high frequency hissing sounds associated with air leaks [99]. Ultrasonic leak detection equipment is an essential component to successful leak abatement programs. This equipment facilitates identification of even the smallest leak regardless of the baseline ambient noise level in an industrial plant [100–102]. Fig. 10 shows an ultrasonic leak detection probe.

2.3.3.1. Energy-saving formulations. According to references [13,104], about 20% energy can be saved in compressed-air systems. Using this assumption, energy savings through leak prevention can be expressed as

$$\text{AEScs_leak} = \text{AEU} \times \%\text{ES} \tag{5}$$

Percentage leak can be estimated using Eq. (6) as well:

$$\text{Leakage}\,(\%) = \left[\frac{T \times 100}{T + t}\right] \tag{6}$$

$$\text{Leakage}\,(\text{cfm free air}) = \left[\frac{V \times (P_1 - P_2)}{T \times 14.7}\right] \times 1.25 \tag{7}$$

2.3.4. Energy savings using outside intake air

The air that is supplied to the compressor's intake port is drawn from the compressor room. Because air expands at higher temperatures, the compressors have to work harder to compress this hot, expanded air. This decreases the efficiency of the air compressors. Using cooler outside air can reduce compressor work [9]. If air flow is kept constant, reducing the inlet air temperature

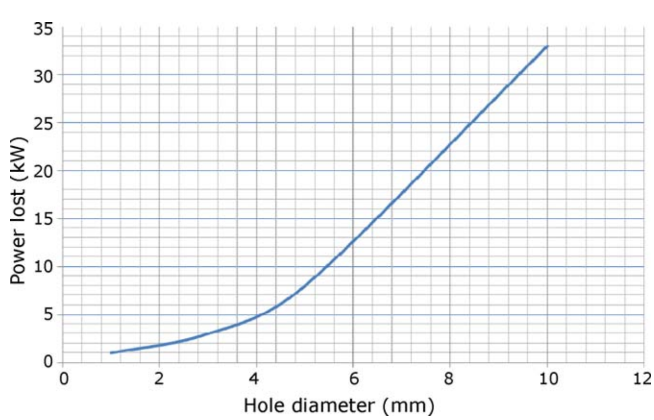


Fig. 9. Dependence of power loss on hole diameter at 600 kPa [9].

reduces energy used by the compressor. In many plants, it is possible to reduce inlet air temperature to the compressor by taking suction from outside the building. As a rule of thumb, each 3 °C will save 1% compressor energy [36,37].

2.3.4.1. Energy-saving formulations. The compressor work for the usual operating conditions in manufacturing plants is proportional to the absolute temperature of the intake air. Thus, the fractional reduction in compressor work, W_R; resulting from lowering the intake air temperature is estimated as [9]:

$$W_R = \frac{W_I - W_R}{W_I} \tag{8}$$

$$W_R = \frac{T_I - T_O}{T_I + 273} \tag{9}$$

where W_I is the work of compressor with inside air, kW; W_O the work of compressor with outside air, kW; T_I the average temperature of inside air, °C; T_o is the annual average outside air temperature, °C.

Annual energy savings (AES_{ia}) associated with the usage of outside intake air temperature can be expressed as

$$AES_{ia} = \text{hp} \times L \times 0.746 \times \text{hr} \times W_R \tag{10}$$

2.3.5. Energy savings due to pressure drop

In many cases, system pressure can be lowered, thereby saving energy. Most systems have one or more critical applications that determine the minimum acceptable pressure in the system. The hissing of the air leaks can sometimes be heard even in high-noise manufacturing facilities. Pressure drops at end-use points in the order of 40% of the compressor-discharged pressure are not uncommon. Yet a common response to such a problem is the installation of a larger compressor instead of checking the system and finding out what the problem is. The latter corrective action is usually taken only after the larger compressor also fails to eliminate the problem. The energy wasted in compressed-air systems because of poor installation and maintenance can account for up to 50% of the energy consumed by the compressor, and it is believed that about half of this amount can be saved by practising energy conservation measures [9,43].



Fig. 10. Ultrasonic leak detector [103].

It is prudent to operate compressed-air systems at the lowest functional pressure that meets production requirements. When pressure supply is higher than required, greater volumes of air are expelled for any given end use, which equates to wasted energy. The standard rule of thumb is that reducing pressure settings by 13 kPa will reduce energy consumption by 1% [100,101].

2.3.5.1. Energy-saving formulations. Energy savings due to pressure drop can be estimated as

$$AES_{pd} = hp \times L \times 0.746 \times hr \times (1 - FR_i) \tag{11}$$

where FR_i is the ratio of proposed power consumption to current power consumption (used to represent a reduction in run time) based on maximum operating pressure.

The following Eq. (12) can be used to estimate FR, the horsepower reduction factor, based on current and proposed operating pressures [9]:

$$FR_i = \frac{((P_{dp} + P_i)/P_i)^{k-1/k} - 1}{((P_{dc} + P_i)/P_i)^{k-1/k} - 1} \tag{12}$$

where P_{dp} is the discharge pressure at proposed operating pressure conditions, kPa; P_{dc} the discharge pressure at current pressure conditions, kPa; P_i the inlet pressure (atmospheric pressure), kPa; k the ratio of specific heat for air ($k = 1.4$).

2.3.6. Energy savings from heat recovery

As much as 80–93% of the electrical energy used by an industrial air compressor is converted into heat. In many cases, a properly designed heat recovery unit can recover anywhere from 50 to 90% of this available thermal energy and put it to useful work in heating air or water. Typical uses for recovered heat include supplemental space heating, industrial process heating, water heating, makeup air heating, and boiler makeup water preheating [45–47,104].

A recuperator can be used to recover waste heat from compressed-air system. In a recuperator, heat exchange takes place between the flue gases and the air through metallic or ceramic walls. Duct or tubes carry the air for combustion to be pre-heated, the other side contains the waste heat stream [48].

2.3.6.1. Energy-saving formulations. Annual energy savings associated with heat recovery can be expressed as

$$AES_{HR} = hp \times L \times 0.746 \times hr \times HRF \tag{13}$$

where HRF is heat recovery factor (0.80 in this case based on Ref. [48]).

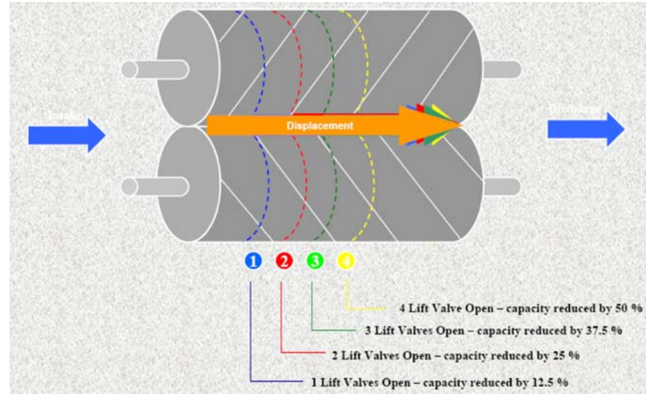


Fig. 11. Energy savings by variable displacement compressor [50].

2.3.7. Energy saving by efficient nozzles

High-velocity air streams create a partial vacuum in the surrounding space, which entrains ambient air into the stream. This effect occurs with all air streams, including compressed air exiting an open tube. This effect can be enhanced by specially designed nozzles that amplify the flow of compressed air by up to 25 times [43]. Air-saver nozzles have smaller discharge areas than intake areas; thus, the flow of compressed air from an open tube is reduced by installing an air-saver nozzle. Replacing the old nozzles with new, air efficient types significantly reduced air usage [49]. Zuercher [50] reported that efficient nozzles can reduce energy consumption by 30–60%.

2.3.8. Variable displacement compressor operation

Variable displacement compressor shows superior performance, smooth operating and energy savings. By opening one or more "lift valves" the variable displacement compressor simulates shorting the length of the rotors; therefore, shorting the stroke and reducing the power requirement at part load capacities. The most important gain achieved by using variable capacity compressors is reduction of energy consumption, which is achievable in a number of different ways, as shown in Fig. 11 [50].

2.3.9. Keep the compressor and intercooling surfaces clean

In a compressed-air system, air contaminants such as dirt, moisture, oil, hydrocarbons gases and bacteria aggressively attack, corrode and erode the piping system, controls, instruments and tools. Maintenance and repair costs may therefore escalate dramatically. Compressed air filters are used to remove water, oil, oil vapor, dirt, and other contaminants from a compressed air supply system [72]. Blocked filters increase pressure drop, and increase annual energy consumption. About 1% in higher energy costs results from every 2 psi in filter pressure drop [10]. Fixing improperly operating filters will also prevent contaminants and reduce energy consumption [105].

Condensate traps collect and remove liquids from compressed-air systems. Traps are located where moisture collects and at low points in the distribution system. Improperly functioning or ineffective condensate traps waste energy and compromise system performance. Manually operated condensate traps are the least efficient because they require continual diligence and adjustment for proper operation. Mechanical float-type and electronic solenoid-operated condensate traps are more efficient. These condensate traps also require periodic inspection to ensure that they do not fail. Condensate traps that fail open (i.e. have drain valves stuck in the open position) waste energy because they allow compressed air to escape into the atmosphere. Condensate traps that fail closed (have drain valves stuck in the closed position) cause condensate to back up in the

system, which can damage components and lead to pressure drop [32].

Inadequate maintenance can lower compression efficiency and increase air leakage or pressure variability, and lead to increased operating temperatures, poor moisture control and excessive contamination. Better maintenance will reduce these problems and save energy. Proper maintenance includes the following [101,106]:

- Blocked pipeline filters increase pressure drop. Keep the compressor and intercooling surfaces clean and foul-free by inspecting and periodically cleaning filters. Fixing improperly operating filters will also prevent contaminants from entering into tools and causing them to wear out prematurely. Generally, when pressure drop exceeds 2–3 psig replace the particulate and lubricant removal elements. Inspect all elements at least annually. Also, consider adding filters in parallel that decrease air velocity and, therefore, decrease pressure drop. A 2% reduction of annual energy consumption in compressed-air systems can be expected by more frequently changing filters [53]. However, one must be careful when using coalescing filters; efficiency drops below 30% of design flow [46].
- Poor motor cooling can increase motor temperature and winding resistance, shortening motor life, in addition to increasing energy consumption. Keep motors and compressors properly lubricated and cleaned. Compressor lubricant should be sampled and analyzed every 1000 h and checked to make sure it is at the proper level. In addition to energy savings, this can help avoid corrosion and degradation of the system.
- Inspect fans and water pumps for peak performance.
- Inspect drain traps periodically to ensure they are not stuck in either the open or closed position and are clean. Some users leave automatic condensate traps partially open at all times to allow for constant draining. This practice wastes substantial amounts of energy and should never be undertaken. Instead, install simple pressure driven valves. Malfunctioning traps should be cleaned and repaired instead of left open. Some automatic drains or valves do not waste air, such as those that open when condensate is present. According to vendors, inspecting and maintaining drains typically has a payback period of less than 2 years [23].
- Maintain the coolers on the compressor and the aftercooler to ensure that the dryer gets the lowest possible inlet temperature [23].
- If using compressors with belts, check the belts for wear and adjust them. A good rule of thumb is to adjust them every 400 h of operation.
- Check water cooling systems for water quality (pH and total dissolved solids), flow and temperature. Clean and replace filters and heat exchangers per manufacturer's specifications.
- Minimize leaks (see also leaks section, below).
- Specify pressure regulators that close when failing.
- Applications requiring compressed air should be checked for excessive pressure, duration or volume. They should be regulated, either by production line sectioning or by pressure regulators on the equipment itself. Tools not required to operate at maximum system pressure should use a quality pressure regulator. Poor quality regulators tend to drift and lose more air. Otherwise, the unregulated tools operate at maximum system pressure at all times and waste excess energy. System pressures operating too high also result in shorter tool life and higher maintenance costs. Automatic valves were installed in one automobile plant (U.S.) to separate production-line sections of the compressed air network from the main supply. They reduced off-shift compressed air use by 40%, saving more than 10,000 kWh for a single weekend shutdown [29]. Case studies show an average payback period for reducing pressure to the minimum required for compressed air applications of about 3 months [107].

2.3.10. Mathematical formulations of payback period

A simple payback period (SPP) for various energy-saving strategies can be calculated by using Eq. (14):

$$\text{Simple payback period (years)} = \frac{\text{Incremental cost}}{\text{Annual dollar savings}} \quad (14)$$

It may be stated that an SPP is easy to understand and communicate. However, SPP ignores the time value of money, fail to consider the riskness of the project, requires an arbitrary cutoff point, ignores cash flows beyond the cutoff, and biased against long-term projects [41].

2.3.10.1. Payback period with cash flow. *Net savings*: In this method, the incremental cost is spreadover the lifetime of the electric motors so that the pattern of expenditures matches the flow of bill savings. This methods smooths the net savings over time. The annualizednet dollar savings in a particular year, which is the main economic indicator used in this analysis, is calculated using the following equation [108]:

$$\text{ANS}_i^{ca} = \text{ES}_i^{ca} \times \text{PF}_i^{ca} - \sum_{i=s}^{T} \text{AS}_i^{ca} \times \text{CRF} \times \text{SF}_i^{ca} \times \text{IIC}^m \quad (15)$$

Cumulative present value: The cumulative present value can be calculated using a percentage real discount rate. The cumulative present value of annualizednet savings can be expressed in the mathematical form as follows [108]:

$$\text{PV}(\text{ANS}_i^{ca}) = \sum_{i=s}^{T} \frac{\text{ANS}_i^{ca}}{(1+d)^{(i-Ydr)}} \quad (16)$$

2.3.11. Emissions mitigation

The environmental impact of the standard is the potential reduction of greenhouse gasses or other elements that cause negative impact on environment. The common emission pollutants that can be reduced are carbon dioxide, sulfur dioxide, nitrogen oxide and carbon monoxide. The impact can be considered a benefit for the society as well. Potential emissions mitigation by standard can be calculated using the following equation [52]:

$$\text{ER}_i^a = \text{ES}_i^a \times (\text{PE}_i^1 \times \text{Em}_p^1 + \text{PE}_i^2 \times \text{Em}_p^2 + \text{PE}_i^3 \times \text{Em}_p^3 + \cdots + \text{PE}_i^n \times \text{Em}_p^n) \quad (17)$$

Table 8 shows emission factors for per-unit energy, that can be used to estimate reducible emission.

The cost of avoided carbon can be estimated using following equation:

$$\text{Cost} = T_{CO_2} \times C_F \quad (18)$$

Cost factor (C_F = US\$53/ton CO_2) can be used as can be found in [109].

Table 8
Emission factors of fossil fuels for electricity generation [52].

Fuels	Emission factor (kg/kWh)			
	CO_2	SO_2	NO_x	CO
Coal	1.18	0.0139	0.0052	0.0002
Petroleum	0.85	0.0164	0.0025	0.0002
Gas	0.53	0.0005	0.0009	0.0005
Hydro	0.00	0.000	0.0000	0.0000
others	0.00	0.000	0.0000	0.0000

3. Computer tools for compressed air analysis

3.1. AIRMaster+ [110]

AIRMaster+, developed by the U.S. Department of Energy (DOE) Industrial Technologies Program (ITP), provides a systematic approach for assessing the supply-side performance of compressed-air systems. Using plant-specific data, the software effectively evaluates supply-side operational costs for various equipment configurations and system profiles. It provides useful estimates of the potential savings to be gained from selected energy efficiency measures and calculates the associated simple payback periods.

AIRMaster+ includes a database of generic or industry-standard compressors and creates an inventory specific to one's actual, in-plant air compressors need. Based on user-provided data, the software simulates existing and modified compressed-air system operations. It can model part-load system operations for an unlimited number of rotary screw, reciprocating, and centrifugal air compressors operating simultaneously with independent control strategies and schedules.

Powerful software features facilitate development of 24-h metered airflow or power data load profiles for each compressor; calculation of life-cycle costs; input of seasonal electric energy and demand charges; and tracking of maintenance histories for systems and components.

AIRMaster+ also includes LogTool, companion software that serves as a data importation and analysis aid. The tool helps users import data that is exported from different types of data loggers; select logger data channels and modify their properties (e.g., name, type, units, etc.); view data values for one or more logger channels; display trend plots with one or two *Y* axes; display scatter plots; and display daytype plots in the format that is needed for AIRMaster+.

3.2. AirSim

The software, AirSim [111], is useful to estimate savings from proposed energy conservation retrofits. AirSim is designed in such a way so that the software output can be visually calibrated to measured energy consumption and/or pressure data. Once calibrated, system parameters can be changed to simulate expected compressor performance under various conditions, and savings can be estimated as the difference between current and expected compressor energy use. The use of the AirSim is thus analogous to the use of building energy simulation software for estimating retrofit savings in buildings.

A primary difference between AirSim and the popular AirMaster+ software is the data time interval for simulation. AirSim allows the user to define a time interval appropriate for the system being considered, where AirMaster+ operates on a fixed time interval of 1 h. Thus, in AirSim, the data time interval can be defined short enough to model actual load/unload or modulation events, which typically occur on the order of seconds or minutes. This feature makes calibration easy, allows the user to develop a better understanding of the dynamic behavior of the system, and allows AirSim to consider savings opportunities, such as auto shutoff, which cannot be modeled using AirMaster+ [111,112].

4. Review results and discussions on compressed-air energy savings, payback periods, and associated emission reductions

Based on the results presented by [15] in Table 9 and by analyzing data, it was determined that 1765, 2703, and 3605 MWh of total energy can be saved by using energy-efficient motors for 50, 75 and 100% motor loading, respectively. Similarly, associated bill savings for the estimated amount of energy savings are US$115,936 US$173,019 and US$230,693, respectively. It also has been found that the payback period for using energy efficient motors ranges from 0.53 to 5.05 years for different percentages of motor loading. These payback periods indicate the introduction/implementation of energy-efficient motors would seem cost-effective, as their payback periods are less than one third of the motor life (if average motor life 20 years is considered) in some cases.

Kaya et al. [112], also carried out some works on compressed air motor energy savings and their outcome in terms of savings (i.e. demand savings, DS, usage savings, US and cost savings, CS) are presented in Table 10.

From Table 11, it is evident that a huge amount of energy can be saved for different percentages of speed reductions. More energy can be saved for higher speed reductions. Along with energy savings, a substantial amount in expense can be saved and associated emission reductions can be achieved using VSD for industrial motors in Malaysia as can be found in Tables 12 and 14. From Table 13, it can be seen that the payback period for larger motors is economically very viable, since the payback period is very short [15].

However, VSD is not cost effective for smaller motors as their payback period is significantly high, as reported by other

Table 9
Energy savings and payback period for high efficient motor [15].

HP	Quantity (No)	Incremental price (US$)	Load (50%)			Load (75%)			Load (100%)		
			Energy savings (MWh)	Bill savings (US$/year)	Payback (year)	Energy savings (MWh)	Bill savings (US$/year)	Payback (year)	Energy savings (MWh)	Bill savings (US$/year)	Payback (year)
1	3,968	24	74	4,730	2.05	96	6,118	1.59	127	8,158	1.19
1.5	331	21	6	394	1.80	7	458	1.55	10	611	1.16
2	1,653	25	28	1,814	2.25	53	3,421	1.19	71	4,562	0.89
3	2,976	27	122	7,798	1.02	174	11,155	0.71	232	14,873	0.53
4	13,556	60	393	25,169	3.22	620	39,675	2.04	827	52,900	1.53
5.5	331	65	16	1,022	2.10	12	792	2.71	16	1,056	2.04
7.5	661	91	19	1,194	5.05	25	1,598	3.77	33	2,131	2.83
15	165	147	21	1,351	1.80	31	1,957	1.24	41	2,609	0.93
20	3,306	197	404	25,888	2.52	811	51,883	1.26	1081	69,177	0.94
25	992	246	156	9,989	2.44	282	18,046	1.35	376	24,061	1.01
30	331	257	11	682	2.33	82	5,261	1.62	110	7,014	1.21
40	661	231	140	8,938	1.71	123	7,852	1.95	164	10,469	1.46
50	331	281	58	3,721	2.50	152	9,746	0.95	203	12,994	0.71
60	827	574	257	16,417	2.89	130	8,295	5.72	173	11,060	4.29
75	165	518	60	3,862	2.22	106	6,763	1.27	141	9,018	0.95

Table 10
Motor energy savings.

Compressor number	Motor power (kW)	Number of motor	Efficiency of standard motor (%)	Efficiency of high efficient motor (%)	DS (kW)	US (kW)	CS ($)
1	55.95	1	92.1	94.6	1.53	6,633	387
2	22.38	2	90.4	93.2	1.41	6,112	356
3	11.19	2	87.1	92.0	1.30	2,818	180
4	7.46	2	86.4	91.0	0.83	1,799	115
5	7.46	1	86.4	91.0	0.41	1,777	104
Total		8			5.48	19,139	1142

Source: [9].

Table 11
Motor energy savings with VSD for different % of speed reduction [15].

Motor power (HP)	Energy savings (MWh)					
	10% Speed reduction	20% Speed reduction	30% Speed reduction	40% Speed reduction	50% Speed reduction	60% Speed reduction
0.25	114	228	316	378	430	461
0.5	57	114	158	190	215	231
0.75	97	195	270	323	368	394
1	391	782	1,084	1,297	1,475	1,582
1.5	49	97	135	162	184	197
2	325	650	901	1078	1,226	1,315
3	880	1,761	2,441	2,921	3,321	3,561
4	5341	10,682	14,809	17,723	20,151	21,607
5.5	179	357	496	593	674	723
7.5	487	975	1,352	1,617	1,839	1,972
15	251	502	696	833	947	1,016
20	6519	13,038	18,075	21,631	24,594	26,372
25	2437	4,874	6,758	8,087	9,195	9,860
30	975	1,950	2,703	3,235	3,678	3,944
40	2600	5,199	7,208	8,626	9,808	10,517
50	1625	3,250	4,505	5,391	6,130	6,573
60	4904	9,808	13,597	16,272	18,501	19,839
75	1256	2511	3,481	4,166	4,737	5,079

researchers [80,81] as well. Abbott [113] reports that payback periods for VSDs of various motor sizes and categories range from 0.4 years to 1.5 years.

Implementing adjustable speed drives in rotary compressor systems can save 15% of the annual energy consumption [53]. Compared to a fixed drive compressor sized for the same application, a variable speed drive compressor consumes about 35% less power [54].

Christina and Worrell [101] found that electricity savings of 443,332 kWh was achieved by installing VSD in metal plating facility in US. Authors mentioned that the project cost $99,400 to implement, and saved $68,600 annually, providing a simple payback period of 1.5 years. The installation also reduced CO_2 emissions by 213,000 kg/year.

Table 14 shows the emission reduction associated with the energy savings by motors using VSD. So, there are still tremendous potential for energy savings and bill savings for all the industries in Malaysia, along with reduced emissions of pollutants [45].

Table 15 shows the energy, cost savings along with payback period for different strategies of compressed-air energy savings

Table 12
Bill (US$) savings for VSD [15].

Motor power (HP)	Speed reduction					
	10%	20%	30%	40%	50%	60%
0.25	7,295	14,590	20,227	24,205	27,521	29,511
0.5	3,655	7,311	10,135	12,129	13,790	14,787
0.75	6,239	12,478	17,300	20,703	23,539	25,240
1	25,020	50,040	69,373	83,020	94,393	101,216
1.5	3,120	6,239	8,650	10,351	11,769	12,620
2	20,797	41,595	57,665	69,009	78,462	84,134
3	56,342	112,683	156,220	186,952	212,562	227,928
4	341,832	683,664	947,806	1,134,260	1,289,638	1,382,865
5.5	11,439	22,877	31,716	37,955	43,154	46,274
7.5	31,196	62,392	86,498	103,514	117,694	126,202
15	16,071	32,141	44,559	53,325	60,630	65,013
20	417,206	834,412	1,156,799	1,384,366	1,574,005	1,687,789
25	155,980	311,959	432,489	517,569	588,469	631,009
30	62,392	124,784	172,996	207,028	235,387	252,403
40	166,378	332,757	461,322	552,073	627,700	673,076
50	103,986	207,973	288,326	345,046	392,312	420,672
60	313,850	627,700	870,220	1,041,411	1,184,070	1,269,666
75	773,970	1,547,940	2,146,008	2,568,173	2,919,978	3,131,060

Table 13
Payback period for speed reduction with the application of VSD [15].

Motor power (HP)	Payback period (year) for speed reduction					
	10%	20%	30%	40%	50%	60%
0.25	113.79	56.89	41.04	34.29	30.16	28.13
0.5	58.28	29.14	21.02	17.56	15.45	14.41
0.75	39.77	19.89	14.34	11.99	10.54	9.83
1	30.52	15.26	11.01	9.20	8.09	7.54
1.5	21.27	10.63	7.67	6.41	5.64	5.26
2	16.64	8.32	6.00	5.02	4.41	4.11
3	12.02	6.01	4.33	3.62	3.19	2.97
4	9.70	4.85	3.50	2.92	2.57	2.40
5.5	7.81	3.91	2.82	2.35	2.07	1.93
7.5	6.47	3.23	2.33	1.95	1.71	1.60
15	4.62	2.31	1.66	1.39	1.22	1.14
20	4.15	2.08	1.50	1.25	1.10	1.03
25	3.88	1.94	1.40	1.17	1.03	0.96
30	3.69	1.85	1.33	1.11	0.98	0.91
40	3.46	1.73	1.25	1.04	0.92	0.86
50	3.32	1.66	1.20	1.00	0.88	0.82
60	3.23	1.61	1.16	0.97	0.86	0.80
75	3.14	1.57	1.13	0.95	0.83	0.78

measures. It has been observed that payback period for different strategies are economically very viable as it is quite short (i.e. only few months). It can be stated that about 0.5–50% of energy can be saved for different energy savings measures. It was also found that payback periods for these measures are quite short (i.e. 3–24 months) [46].

Table 16 shows energy and cost savings for different types of industry assessed for compressed-air energy savings. It can be stated that a sizeable amount of energy and cost can be saved for compressed-air systems. It has been found that about 75 GWh of energy and US$1.8 million cost can be saved for total number of industries assessed in this study [114].

Energy saving analysis was undertaken in two most promising areas for air compressor systems for strategy (1) optimizing load profile; and (2) preventing air leakages [72]. Results of savings presented in Table 17. Author reported that net present value of US$864,023 can be saved for different energy savings measures. Combining strategy 1 and 2 will save about 1.6 GWh of electrical energy.

Table 18 shows the amount of energy, cost savings and emission reductions of compressed-air system using air efficient nozzles. From the data analysis it has been found that return on investment is immediate as payback period is only about 1 month for energy savings of about 953 MWh [115].

Table 19 shows energy savings, cost savings and emission reductions. It was shown that payback period is economically very viable as it is very short.

Table 20 shows energy and cost savings along with payback period estimation for different energy savings measures. It shows that measures are very cost effective as payback period is very short.

Table 21 shows demand savings, DS, usage savings, US, and cost savings, CS, calculations as a direct result of leak prevention. Implementation of this energy conservation opportunities may involve replacement of couplings and/or hoses, replacement of seals around filters, shutting off air flow during lunch or break periods, or repairing breaks in lines. Assuming that this work can be done by facility maintenance personnel, it is estimated that all 14 leaks in the plant can be eliminated for 5$280 ($20 per leak). Thus, the cost savings of $2627/year will pay for the implementation cost within approximately 2 months [9].

Table 22 Shows demand savings, DS, usage savings, US, and cost savings, CS, calculations as a direct result of reducing compressor air pressure. Assuming that these adjustments can be done by the

Table 14
Emission reductions associated with energy savings by VSD [15].

Motor power (HP)	Emission reductions (kg) for 20% speed reduction				Emission reductions (kg) for 40% speed reduction				Emission reductions (kg) for 60% speed reduction			
	CO_2	SO_2	NO_x	CO	CO_2	SO_2	NO_x	CO	CO_2	SO_2	NO_x	CO
0.25	1,140,634	6,828	3,217	694	1,892,415	11,328	5,337	1,151	2,307,191	13,811	6,506	1,403
0.5	570,194	3,413	1,608	347	946,003	5,663	2,668	575	1,153,346	6,904	3,252	702
0.75	978,003	5,854	2,758	595	1,622,596	9,713	4,576	987	1,978,233	11,842	5,579	1,203
1	3,911,026	23,411	11,029	2,379	6,488,748	38,842	18,298	3,947	7,910,939	47,355	22,309	4,812
1.5	489,371	2,929	1,380	298	811,911	4,860	2,290	494	989,864	5,925	2,791	602
2	3,258,531	19,506	9,189	1,982	5,406,200	32,361	1,5245	3,288	6,591,120	39,454	18,587	4,009
3	8,799,809	52,676	24,815	5,352	14,599,683	87,394	41,171	8,880	17,799,614	106,548	50,195	10,826
4	53,445,435	319,924	150,716	32,507	88,670,836	530,783	250,052	53,932	108,105,540	647,119	304,858	65,753
5.5	1,794,361	10,741	5,060	1,091	2,977,008	17,820	8,395	1,811	3,629,502	21,726	10,235	2,208
7.5	4,886,319	29,249	13,779	2,972	8,106,847	48,528	22,861	4,931	9,883,690	59,164	27,872	6,012
15	2,439,463	14,603	6,879	1,484	4,047,291	24,227	11,413	2,462	4,934,369	29,537	13,915	3,001
20	65,170,629	390,111	183,781	39,639	108,123,998	647,230	304,910	65,764	131,822,409	789,089	371,739	80,178
25	24,443,914	146,321	68,932	14,868	40,554,676	242,760	114,364	24,667	49,443,372	295,968	139,430	30,073
30	9,787,422	58,587	27,601	5,953	16,238,223	97,202	45,792	9,877	19,797,286	118,506	55,828	12,041
40	26,060,366	155,997	73,490	15,851	43,236,517	258,814	121,927	26,298	52,713,014	315,540	148,651	32,062
50	16,312,370	97,646	46,001	9,922	27,063,705	162,003	76,320	16,461	32,995,476	197,511	93,047	20,069
60	48,907,541	292,760	137,919	29,747	81,142,057	485,716	228,821	49,353	98,926,617	592,174	278,973	60,170
75	12,197,316	73,013	34,396	7,419	20,236,456	121,135	57,067	12,308	24,671,844	147,686	69,575	15,006

Table 15
Energy savings associated with different measures [46].

Source	Measure (IAC recommendation rate)	Average energy savings	Average annual cost savings (payback)
All efficiency improvements			
Rule 1	Implement typical efficiency improvements, which may include many or all of the measures below	20–50%	
Rule 2	Implement typical efficiency improvements, which may include many or all of the measures below (68%)	4% of total facility energy use	$4300 (5 months)
Use cooler outside air			
Rule 3	Use cooler air for intakes	1% per 5 °F reduction	Less than 2 years
Rule 4	Use cooler air for intakes (37%)	0.2% of total facility energy use	$1400 (5 months)
Optimize load			
Rule 5	Install or adjust unloading controls	10%	
Rule 6	Upgrade screw compressor controls (1%)	0.8% of total facility energy use	$7900 (10 months)
Reduce compressor air pressure			
Rule 7	Reduce compressor pressure (15%)	0.4% of total facility energy use	$2800 (4 months)
Rule 8	Reduce compressor pressure	1% per 2 psi reduction	
Eliminate/reduce compressed air use			
Rule 9	Eliminate/reduce some uses of air (5%)	0.6% of total facility energy use	$7300 (6 months)
Eliminate air leaks			
Rule 10	Repair air leaks	30% or more	
Rule 11	Repair air leaks (36%)	4% of total facility energy use	$3900 (3 months)
Rule 12	Reduce air leaks in distribution system	0.7% decrease in compressor energy use per 1 psi loss reduction	
Rule 13	Repair 1/16 leak	7560 kWh per leak per year	$360/year
Recover waste heat			
Rule 14	Recover waste heat from compressors (8%)	1.8% of total facility energy use	$2700 (10 months)
Change filters and clean coolers			
Rule 15	Change dryer filters at 8–10 psi drop	0.5% provided 1 psi drop in pressure	
Rule 16	Clean intercoolers to reduce compressor working temperature	1% per 11 °F reduction	

maintenance crew in a few minutes, the implementation cost of adjusting the pressure settings are estimated as zero. Therefore, the energy cost savings is immediate [9]. Table 23 shows potential energy savings for different energy savings measures in EU. Author reported that a total of about 32.9% energy can be saved for different energy savings measures.

From Table 24, it has been found that about 2.6–9% energy can be saved for delivery pressure reduction in compressed-air systems. Table 25 also shows power reduction associated with compressor air pressure reduction.

Table 26 shows annual savings and payback period of compressed air leak prevention.

Table 27 shows the summary of energy, cost savings along with payback periods for compressed-air system in US manufacturing plants.

The payback period resulting from leak prevention is taken from Radgen [13]. The author found that the payback period for leak prevention is about 6 months, which is economically very viable. Yang [72] also reports that the payback period through leak prevention is about 5.14 months in one Vietnamese enterprise. Kuisis [73] reported that cost of leak detection equipment range from US$3680 to US$11,042. Michael et al. [75] reported that average payback period for improving compressed-air system in

Table 16
Compressed-air system savings identified by industry.

Industry (no. of assessments)	Average energy savings (kWh/year)	Average $ savings (annual)
Automotive (32)	12,258,688	212,351
Cement (7)	8,397,537	159,160
Chemical (7)	12,581,126	299,977
Electronics (2)	4,648,671	180,810
Food processing (14)	4,292,989	83,435
Forest products (2)	1,740,320	30,268
General manufacturing (17)	6,950,230	139,337
Glass (7)	10,680,137	471,247
Plastics (3)	2,976,867	54,388
Steel (6)	11,081,884	146,294

Source: [114].

Table 17
Cost-effectiveness analysis for air compressors.

Average price of electricity in 2007 (USD/kWh)	0.0522	Collected on-site in the enterprise
Electricity savings from strategy 1 (kWh/year)	1,018,080	Calculated
Electricity savings from strategy 2 (kWh/year)	3,524,648	Calculated
Total savings of electricity (kWh/year)	4,542,728	Calculated
Capital investment in compressor relocation (USD)	42,500	Calculated
Capital investment in preventing leakage (USD)	41,367	Calculated
Total investment cost (USD)	83,867	Calculated
O & M costs (USD/year)	41,367	On going replacement of broken parts
Total net saving values after first year (USD/year)	1,95,763	Calculated
Payback period (months)	5.14	Calculated
Life time of the newly invested technology (year)	15	Assumed
CO_2 emission factor (kg CO_2 e/kWh)	0.7	Assumed
Discount rate (%)	12	Calculated
CO_2 emission reduction (ton/year)	3,180	Calculated
Internal rate of return (IRR)	184%	Calculated
Net present value (USD)	864,023	Calculated

Table 18
Savings by installing air-saver nozzles.

	Annual savings			Project cost	Simple payback	Investment IRR
	Resource	CO_2 (lb)	Dollars			
Electricity	953,000 kWh	2,200,000	$63,900	$380	1 month	17,000%

Source: [115].

Table 19
Reclaim heat from air compressors.

	Annual savings			Project cost	Simple payback
	Resource	CO_2 (lb)	Dollars		
Electric demand	−17.3 kW		−$1,196		
Electric use	−41,520 kWh	−95,496	−$955		
Gas use	47,120 ccf	527,477	$16,492		
Net		432,248	$14,341	$15,000	13 months

Source: [115].

Table 20
Energy, cost savings and payback period of for different energy savings measures at different types of industries.

Type of plant	Food processing	Food processing	Corrugated box plant
kWh savings	9,25,400/year	1,897,700/year	573,180/year
Energy cost savings	$1,14,000/year	$1,42,300/year	$42,977/year
Project costs	$1,28,000	$1,67,900	$13,140
Simple payback period	1.1 years	1.2 years	0.3 years
Selected measures	• Correct capacity controls • Replace dryers and filters • Add air storage • Correct distribution piping	• Install smaller compressor for non-production uses • Reconfigure pipes to reduce pressure losses • Replace drains with level-activated models	• Correct capacity controls • Remove unneeded dryers from operation • Replace open blow end-users with Venturi amplifiers

Source: [116].

pulp and paper industry through leak prevention about 4 months. CADET [49] reported that payback period for leak prevention program about 8 months. Christina and Worrell [101] reported that the Ford Stamping Plant in Geelong, Victoria (Australia) used an ultrasonic inspection tool to search for leaks. After repairs of the leaks, they saved over US$83,200 per year. Payback periods were less than 1 month. Leak detection and remedial work has a relatively short payback of much less than 1 year [29].

It can be stated that the PVC pipe can be used to supply intake outside air from the compressor's air intake through the outside wall of the compressor room. This will supply the compressors with cooler, denser outdoor air and increase compression

Table 21
Energy and cost savings from repair of air leaks.

Leak diameter (mm)	Numbers of leaks	V_f ($m^3 h^{-1}$)	L (kW)	DS (kW)	US (kWh)	DCS ($ $year^{-1}$)	UCS ($ $year^{-1}$)	CS ($ $year^{-1}$)
0.4	5	2.62	0.3	0.3	1300.5	7	69	76
0.8	2	4.19	0.48	0.48	2081	11	110	121
1.6	6	50.3	5.76	5.76	24969	135	1323	1458
3.2	1	33.53	3.84	3.84	16646	90	882	972
Total	14	90.64	10.38	10.38	44996.5	243	2384	2627

Source: [9].

Table 22
Calculated savings for compressors.

Compressor number	Energy savings (%)	Usage savings (kWh $year^{-1}$)	Usage cost savings ($ $year^{-1}$)	Energy savings (kWh $year^{-1}$)
1	4.2	23,280	1176	23,280
2	2.2	9,079	459	9,079
3	3.0	5,155	260	5,155
4	2.2	3,733	189	3,733
5	6.2	10,634	537	10,634
6	4.9	7,010	354	7,010
Total		58,891	2975	58,891

Source: [9].

Table 23
Energy saving potential based on the EU study [53].

Energy savings measure	% Applicability [X]	% Gains [Y]	Potential contribution [Z]
System installation or renewal			
Improvements of drives (high-efficiency motors, HEM)	25%	2%	0.5%
Improvements of drives (adjustable speed drives, ASD)	25	15%	3.8%
Upgrading of compressor	30%	7%	2.1%
Use of sophisticated control systems	20%	12%	2.4%
Recovering waste heat for use in other functions	20%	20%	4.0%
Improved cooling, drying and filtering	10%	5%	0.5%
Overall system design, including multi-pressure systems	50%	9%	4.5%
Reducing frictional pressure losses	50%	3%	1.5%
Optimizing certain end use devices	5%	40%	2.0%
System operation and maintenance			
Reducing air leaks	80%	20%	16.0%
More frequent filter replacement	40%	2%	0.8%
Total			32.9%

[X]% of CAS where this measure is applicable and cost effective.
[Y]% reduction in annual energy consumption.
[Z]Potential contribution = applicability × reduction.

Table 24
Effect of reduction in delivery pressure on power consumption [12].

Pressure reduction		Power savings (%)		
From (kPa)	To (kPa)	Single-stage water-cooled	Two-stage water-cooled	Two-stage air-cooled
680	610	4	4	2.6
680	550	9	11	6.5

efficiency. The total cost of implementation would be about $380 [105]. Michael et al. [75] reported that average payback period for improving compressed-air system in pulp and paper industry using outside air about 4 months. A payback period of 2–5 years has been reported for importing fresh air [49]. In addition to energy savings, compressor capacity is increased when cold air from outside is used. Case studies taken from the Industrial Assessment Centre (IAC) database have found an average payback period for importing outside air of about 11 months [107]. A sheet metal manufacturer (U.S.) used outside air for compressed air intake and found initial costs to be $400 and a payback period of less than 1 year [118]. Manan [119] found that lowering the inlet temperature by 11 °C would result in an estimated annual energy savings of 550,000 MJ which is equivalent to monetary savings of about RM15,000/year.

The activation pressures of the compressor can easily be adjusted by maintenance personnel by following the instructions in the compressor manual. This task should take no more than 30 min, thus the implementation cost is negligible [9]. As a result payback period is immediate. Michael et al. [75] reported that average payback period for improving compressed-air system in pulp and paper industry reducing pressure drop about 4 months.

Cost of a recuperator to recover waste heat from compressed-air system is about US$25/kW [75]. The payback periods resulting from waste-heat recovery are taken from Radgen [10] and the author found that the payback period for heat recovery is about 6 months, which is economically very viable as well. Michael et al. [75] reported that average payback period for improving compressed-air system in pulp and paper industry by recovering waste heat about 4 months.

Numerous case studies estimate the average payback period for this measure at approximately 1.2 years [75]. An Italian plant producing tappets for cars (levers used in vehicle assembly) used the waste heat gained by cooling the compressed air to heat part of the factory not served by the central heating plant. Payback period was less than 1 year [49]. A metal fabrication plant (U.S.) implementing a heat recovery system had a payback period of 0.3 years for a similar system [118].

Cost of an efficient nozzle is about US$60 [51] and resulting payback periods for using efficient nozzle is found to be in the range of 0.01–2.68 meaning that investment in efficient compressors is economically very sound. Best practice [51] reported that payback period for use of efficient nozzle in their plant about 4 months. Anon [120] also reported that payback period for using efficient nozzle is about 4 months. Michael et al. [75] reported that average payback period for improving compressed-air system in pulp and paper industry using

Table 25
150 hp Reciprocating compressor power consumption data at various exit pressures.

	Exit pressure (kPa)	Pressure ratio	Power (kW)
97.2	876.6	9.0	116.4
97.2	835.2	8.6	116.8
97.2	784.9	8.1	110.5
97.2	747.7	7.7	111.9
96.5	705.0	7.3	109.9
97.2	657.4	6.8	103.2
96.5	607.8	6.3	102.7
96.5	547.8	5.7	99.3
96.5	500.3	5.2	93.0
96.5	452.7	4.7	91.62
96.5	424.5	4.4	90.9

Source: [117].

Table 26
Payback period [12].

	Investment cost (USD)	Annual savings (USD)	Payback
Leakage reduction	6218	9081	9 months
Air efficient nozzles	168	576	4 months

Table 27
Summary of energy, cost savings, cost of project implementation and payback period.

Industry (location)	Energy savings (kWh/year)	Energy savings (US$)	Project cost (US$)	Payback period (months)	Reference
Sanmina Corporation (New work)	742,000	63,000	55,000	10.5	[110]
San Jose	800,000	96,000	129,000	16	[114]
Raytheon Company (Massachusetts)	1,559,000	141,500	168,000	14	[114]
International Truck and Engine Corporation (Indiana)	7,200,000	395,000	800,000	24	[114]
BWX Technologies (Virginia)	4,200,000	264,000	487,000	24	[114]
Bodine Electric company (Illinois)	–	85,000	135,500	19	[114]
Edgar Thomson plant (Pennsylvania)	–	457,000	521,000	14	

efficient nozzle about 4 months. The payback for filter cleaning is usually under 2 years [103].

5. Conclusions

From the review, it has been identified that energy audit is an effective tool that helps to collect data necessary for estimating compressed-air energy use. It also helps to identify where energy waste is taking place so that necessary measures can be implemented. Based on literature review it has been identified that only about 10–20% of total input energy is utilized for useful work in compressed-air system. Major energy lost takes place in the form of waste heat and through the leakage of compressed air. So, these are potential areas where energy savings options can be applied for huge amount of energy recovery in compressed-air system.

Mathematical formulations for different energy savings options have been established that can be used for the estimation of energy, cost savings, emission reductions and payback period. Necessary input parameters to estimate different types of savings have been identified in most cases.

It may also be noted that energy can be saved using high efficient motors instead of standard efficient motors. Many researchers found use of energy efficient motors economically viable based on the estimation of payback period. However, many researchers opined that replacing standard motor with energy efficient motors are not economically attractive for smaller capacities of motors. It was also found that VSDs are used to match the required loads in order to save electrical motor energy in compressed-air system. However, it should be noted that VSDs are economical viable only for large motors [91].

This review could be useful for motor designers, operators, energy managers and motor manufacturers to fully understand energy saving opportunities in electric motors in compressed-air systems and further to take proper energy-saving measures to enhance energy efficiency in industries. They could help designers adopt proper design options and concepts in the decision making process during the initial planning and design stages (i.e. how to reduce losses) and help operators to use advanced control algorithms in practical operations to reduce the global energy consumption in electric motors and enhance control stability and environmental sustainability. It could also be useful for the government to evaluate the current electric motor energy policies.

It was also found that use of energy efficient nozzler, through proper maintenance, by recovering waste heat, using variable displacement compressor sizeable amount of energy and cost can be saved along with reducing environmental emissions. The review also identified two computer tools that can be used for compressed-air energy analysis.

Awareness and education also important instruments those are very usefull in energy savings. Mass media can play an important role by publicizing the benefits of energy savings. It is expected that these attractive measures will motivate industrial-energy users to implement and reduce their cost of energy usage.

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